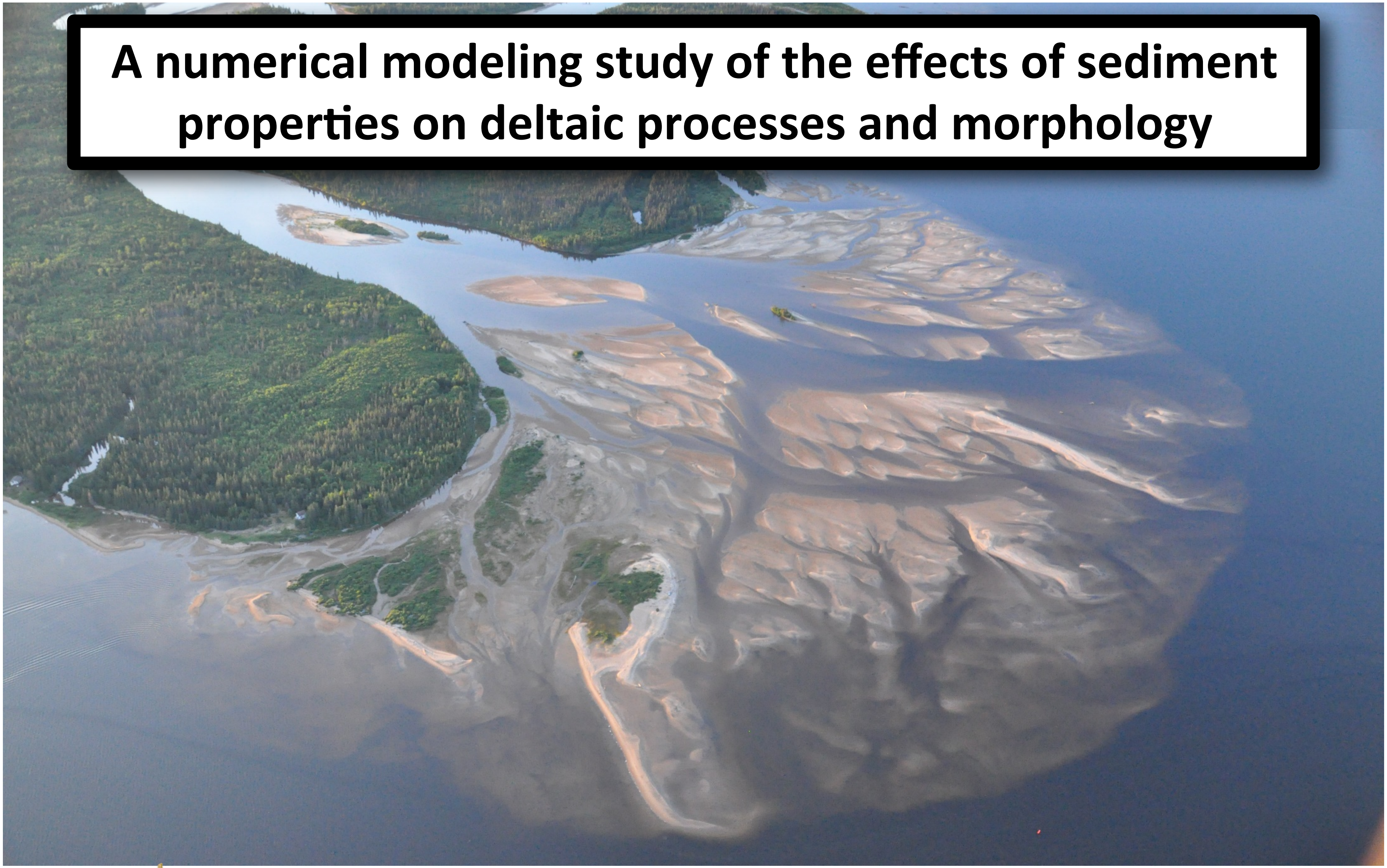
A numerical modeling study of the effects of sediment properties on deltaic processes and morphology



Rebecca Caldwell and Douglas Edmonds
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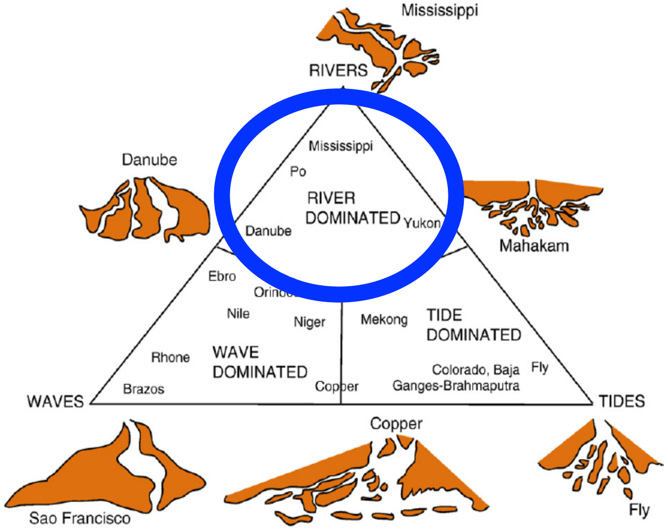
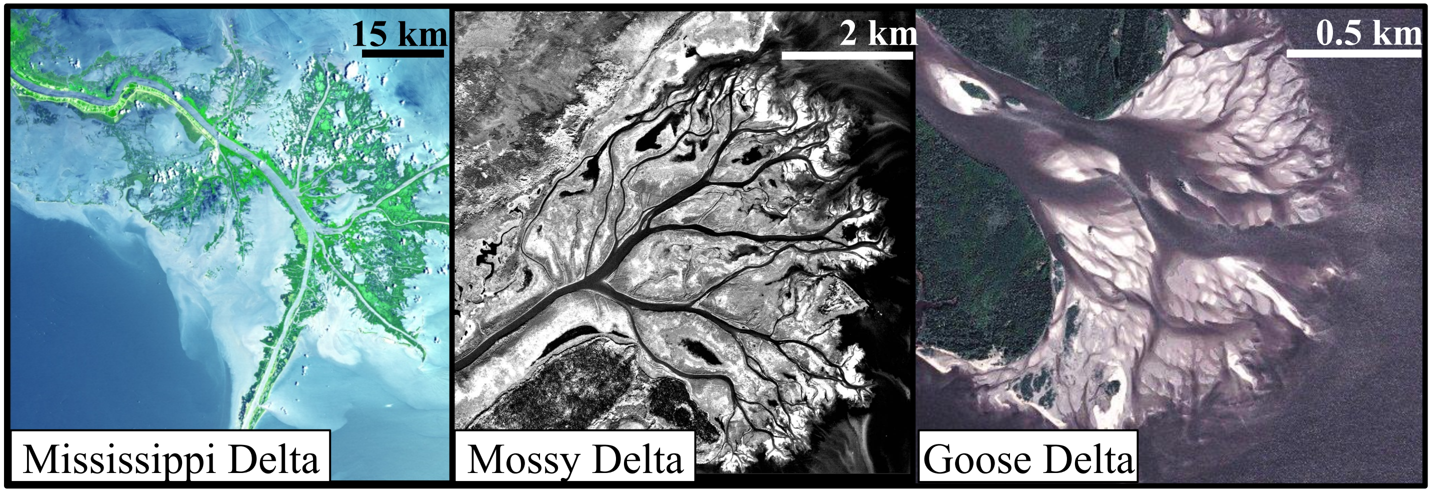
Traditionally, delta morphology has been explained by the relative influence of rivers, waves, and tides



[*Syvitski and Saito,* 2007; after *Galloway,* 1975]



$P_m:P_r = 0.1$	$P_m:P_r = 0.15$	$P_m:P_r = 0.022$
$D_{50} = 0.01$ mm	$D_{50} = 0.125$ mm	$D_{50} = 0.3–0.4$ mm

[calculated after *Syvitski and Saito,* 2007]

How do changes in the grain-size distribution:

(1) Modify delta-building **processes**?

(2) Produce **morphological variation** in the channel network and delta planform?

To model delta growth we use the physics-based model Delft3D to simulate a river entering a standing body of water

Hydrodynamics:

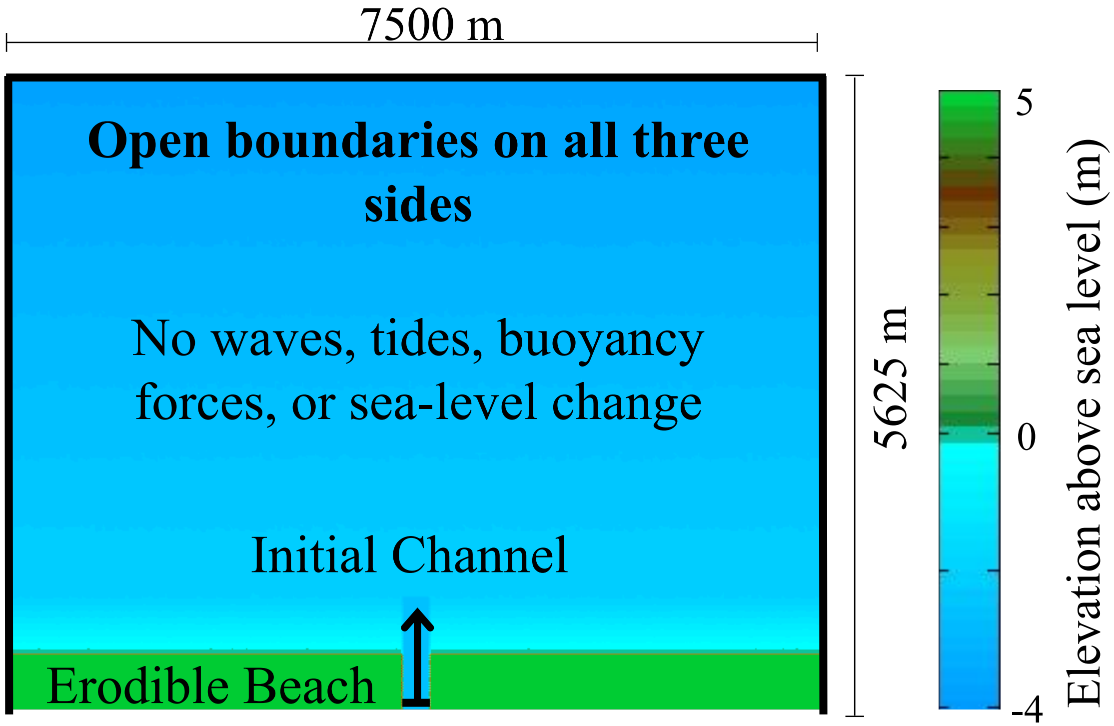
- depth-integrated, RANS equations
- horizontal large eddy simulation

Sediment transport:

- Van Rijn (1993), suspended and bed load
- accounts for bed slope effects

Bed evolution:

- Exner equation
- wetting and drying



Open boundaries on all three sides

No waves, tides, buoyancy forces, or sea-level change

Initial Channel

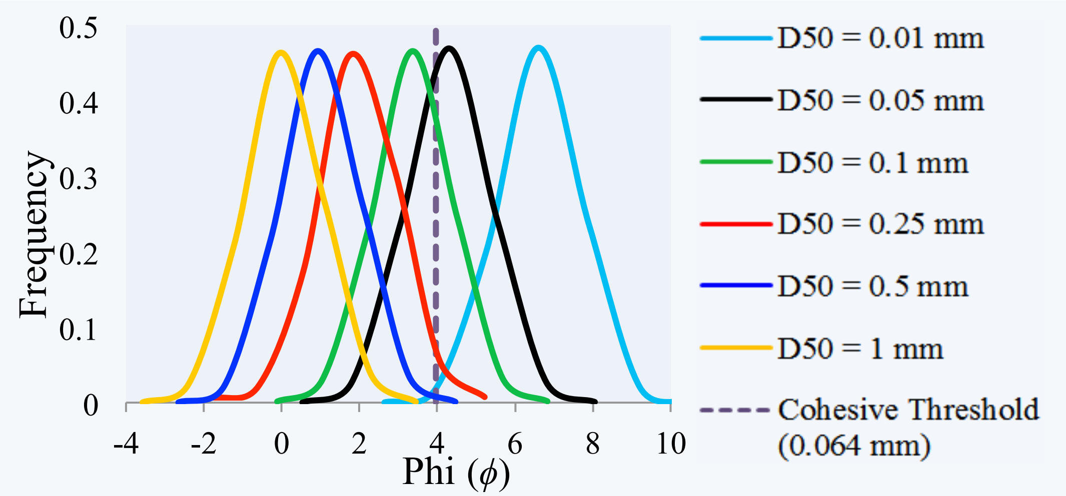
Upstream boundary

Discharge:
1000 m^3/s

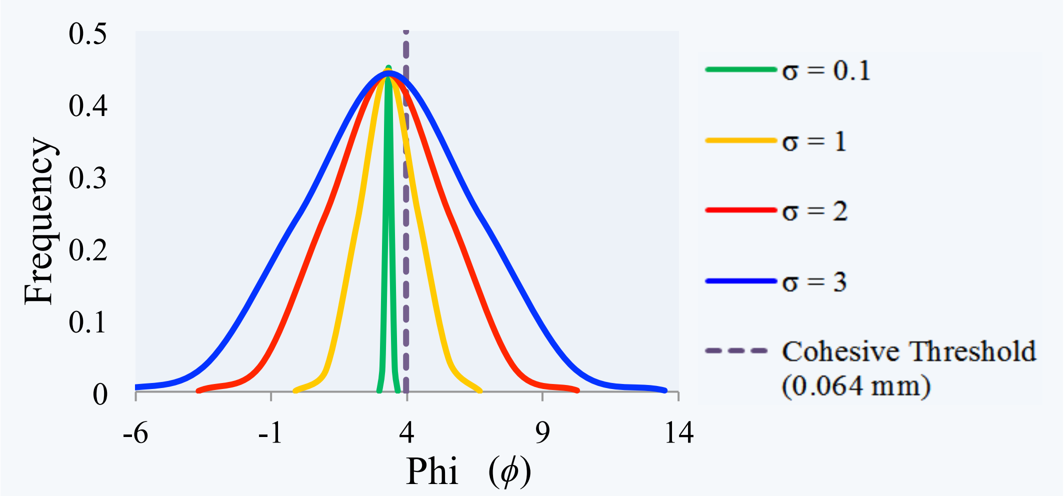
Sediment Flux:
~ 0.04 m^3/s

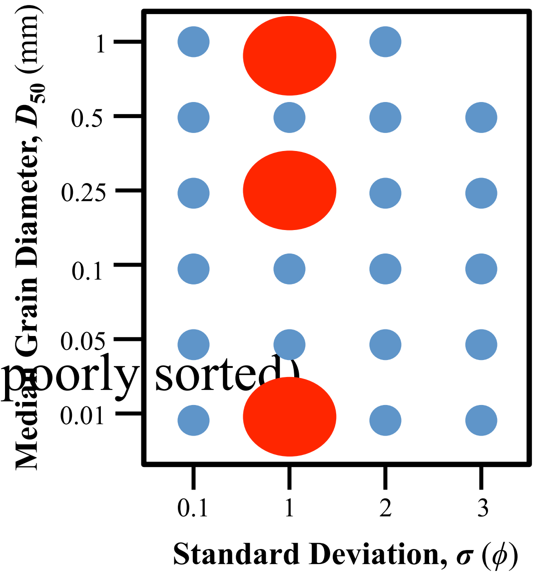
We change the incoming grain-size distribution's median and standard deviation in 23 model runs

Median (D_{50}) → 0.01 mm (silt) to 1 mm (coarse sand)

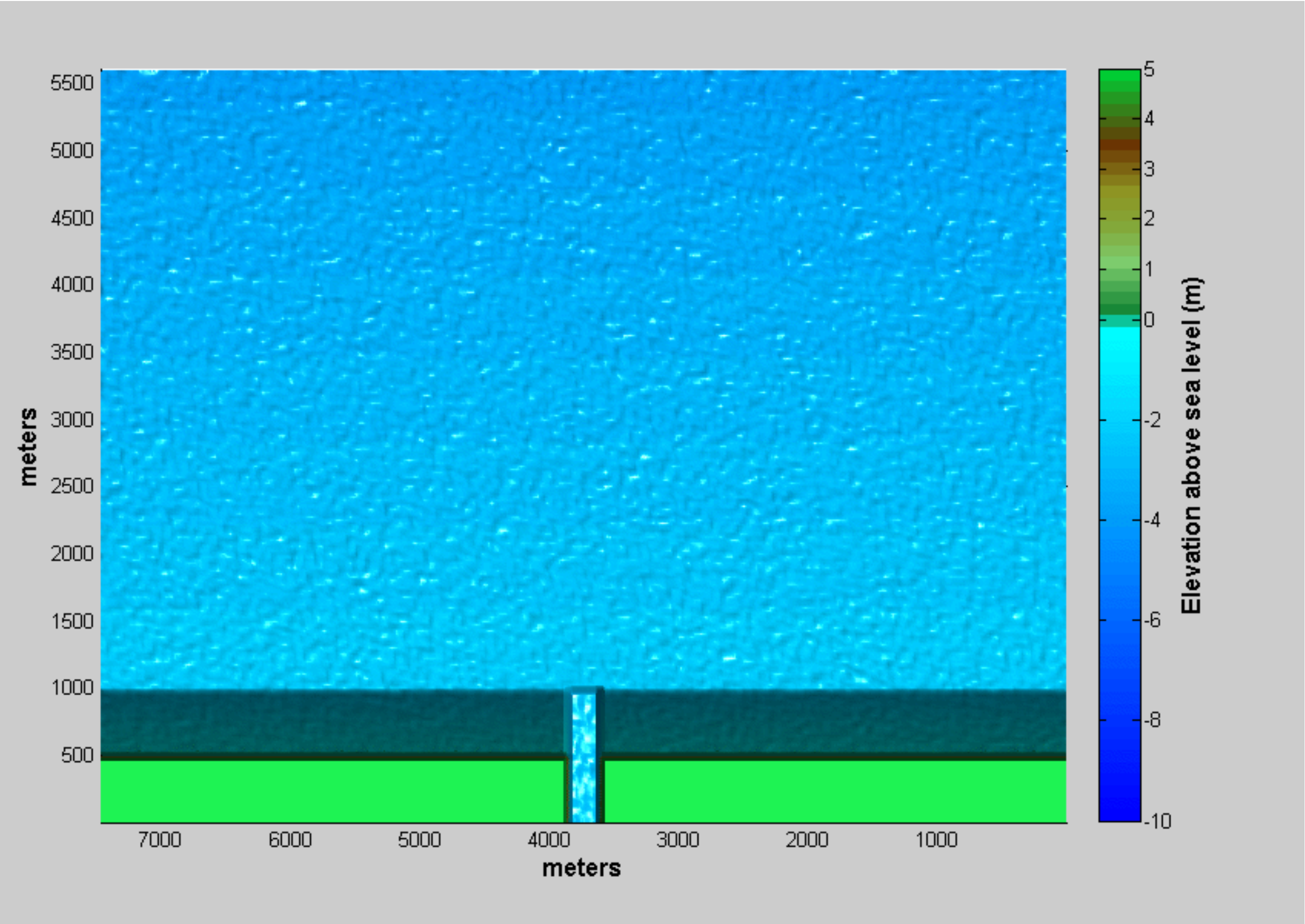


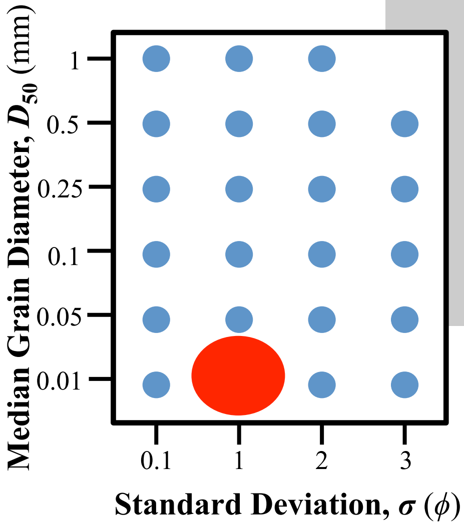
Standard deviation (σ) → 0.1 (very well sorted) to 3 (poorly sorted)





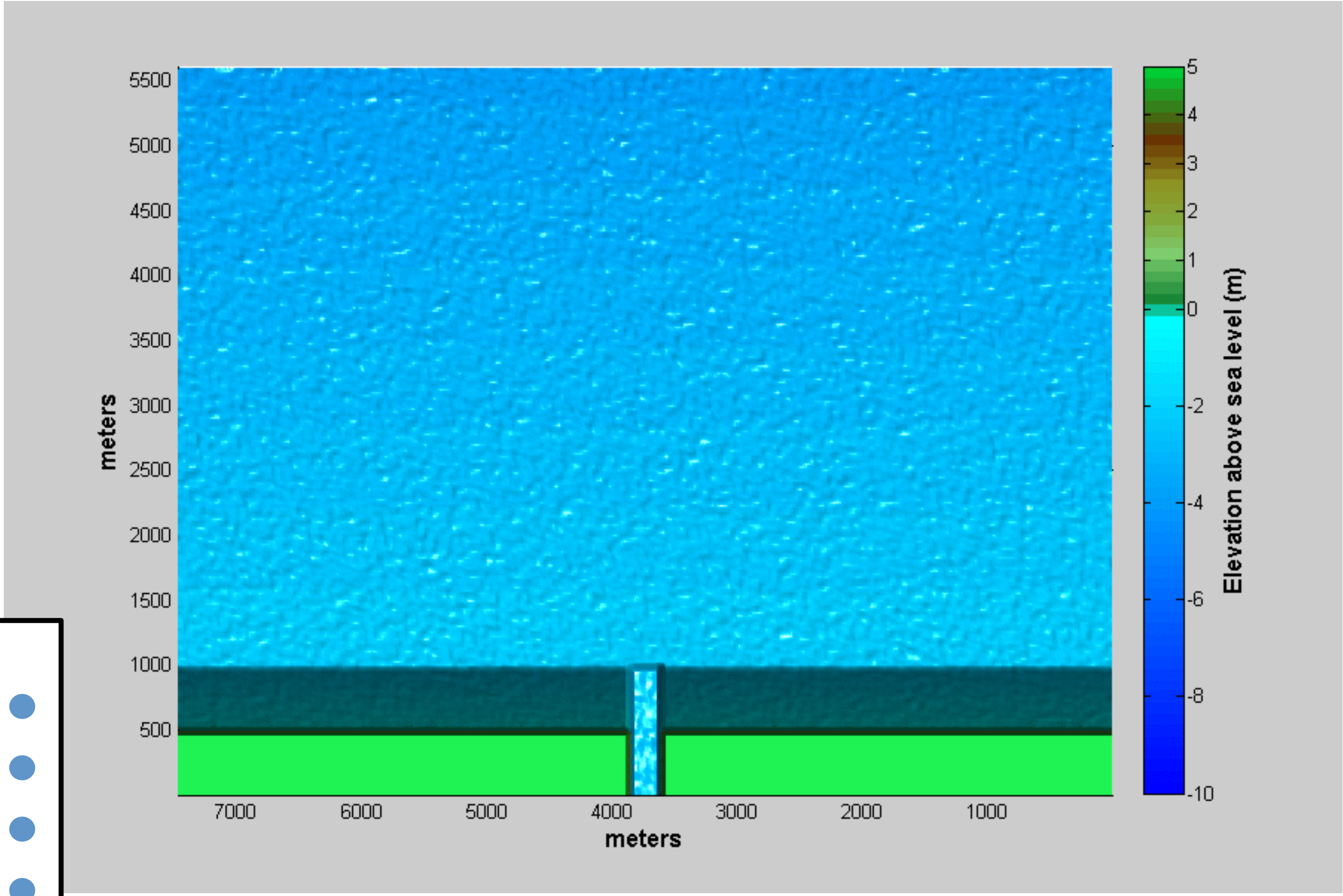
Fine-grained deltas evolve primarily via stable channel elongation

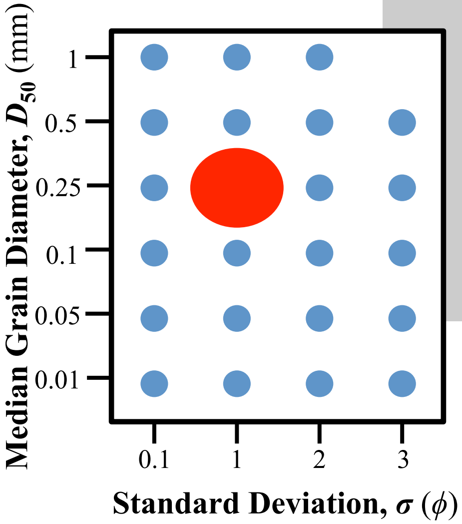




Median (D_{50}) = 0.01 mm, Standard Deviation = 1 ϕ

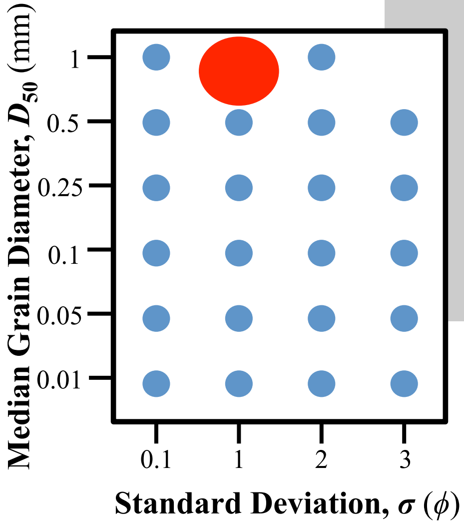
Intermediate-grained deltas evolve via more frequent bifurcations around river mouth bars

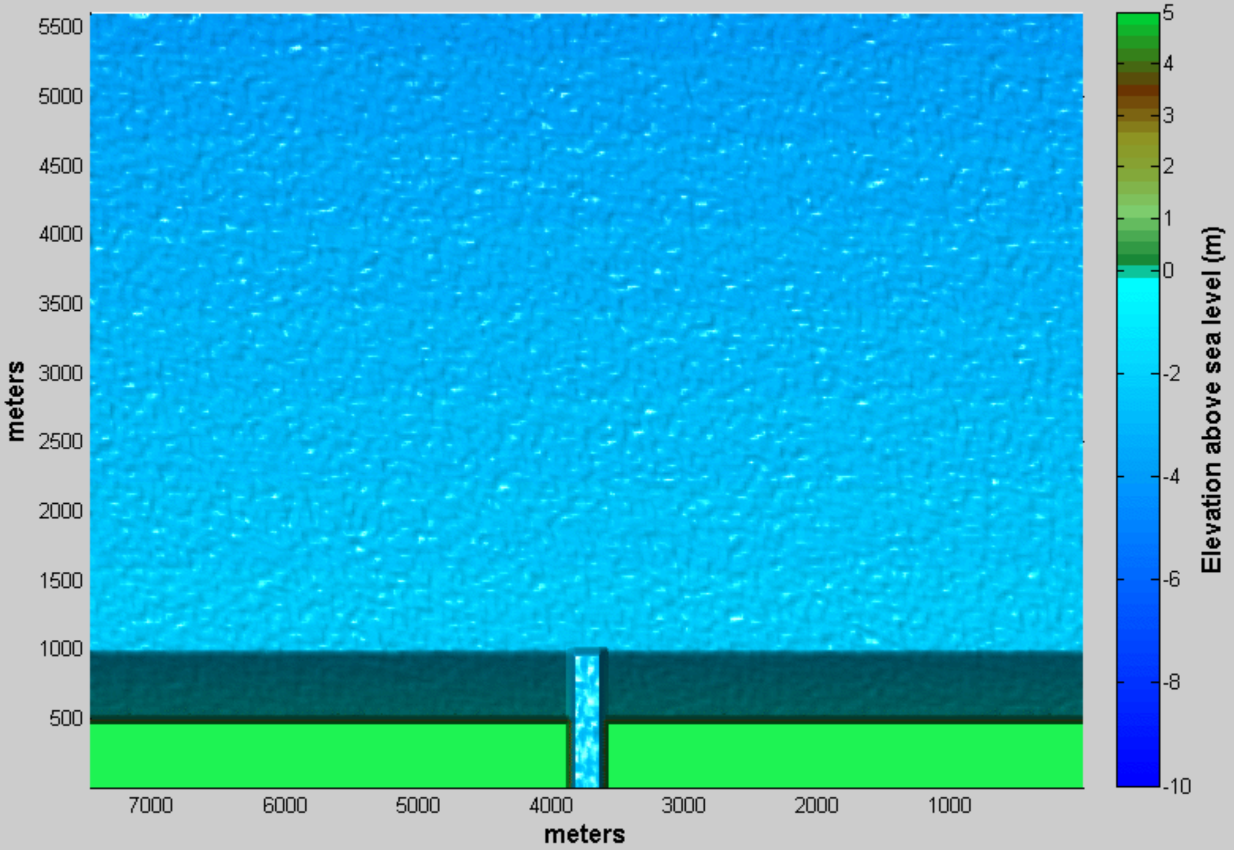




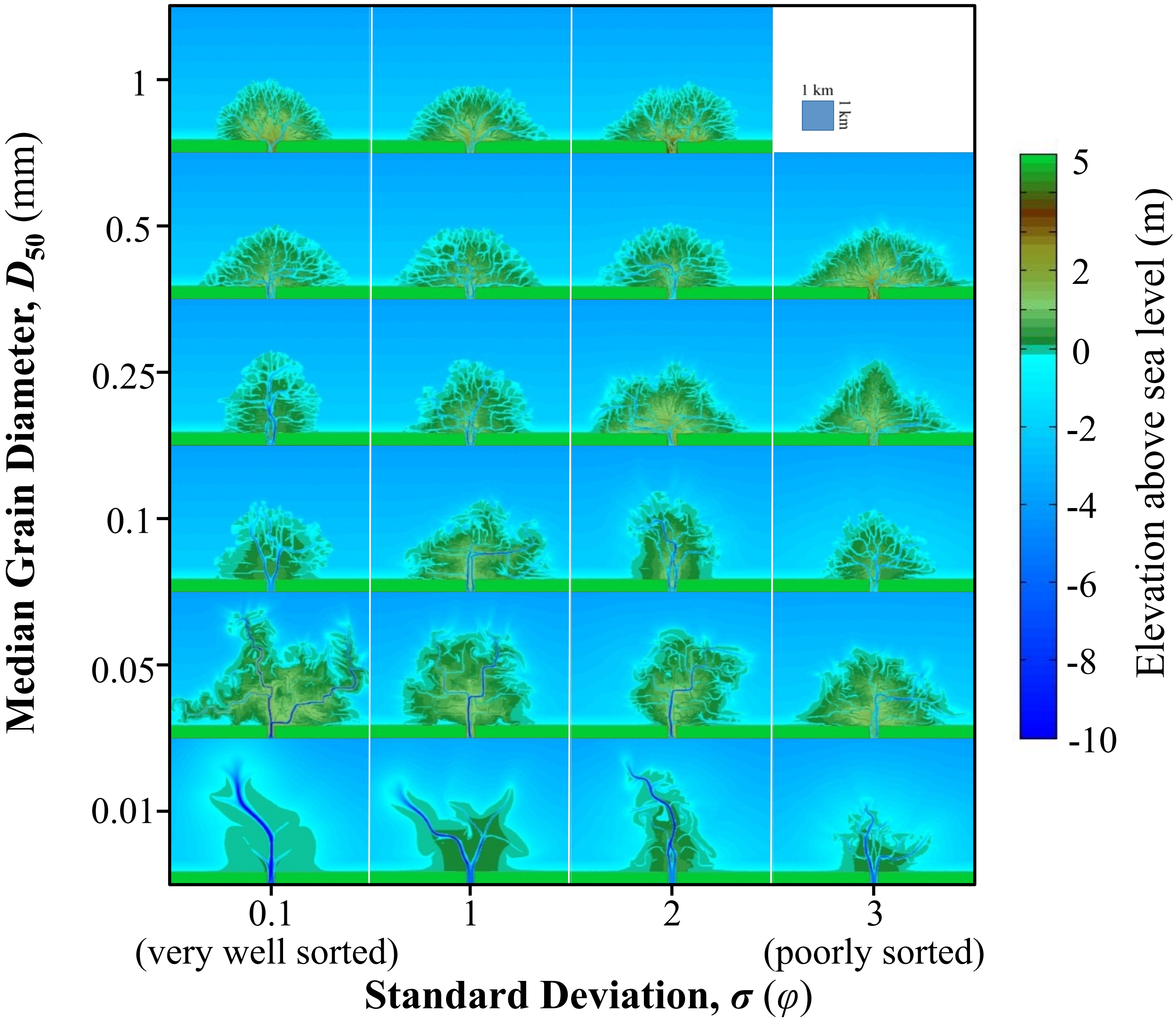
Median (D_{50}) = 0.25 mm, Standard Deviation = 1 ϕ

Coarse-grained deltas evolve via more mobile channels



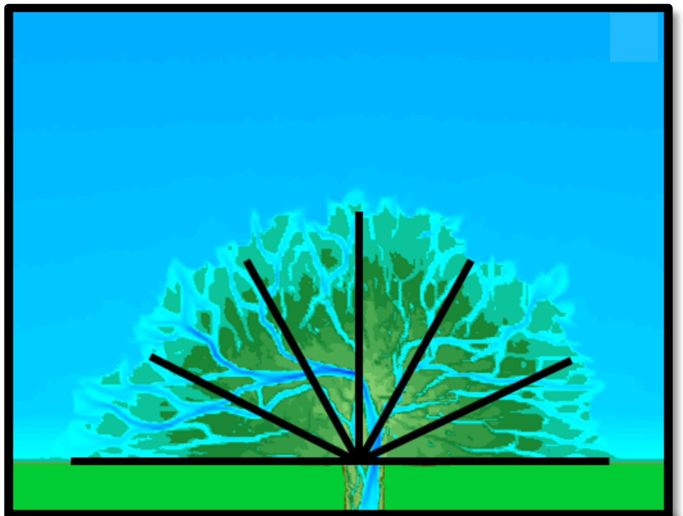


Median (D_{50}) = 1 mm, Standard Deviation = 1 ϕ

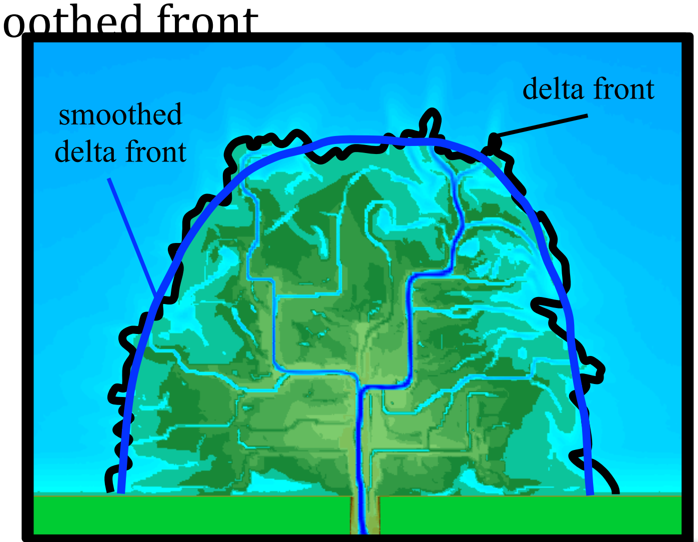

Median Grain Diameter, D_{50} (mm)
1
0.5
0.25
0.1
0.05
0.01
1 km
1 km
0.1
(very well sorted)
1
2
3
(poorly sorted)
Standard Deviation, σ (φ)
5
2
0
-2
-4
-6
-8
-10
Elevation above sea level (m)

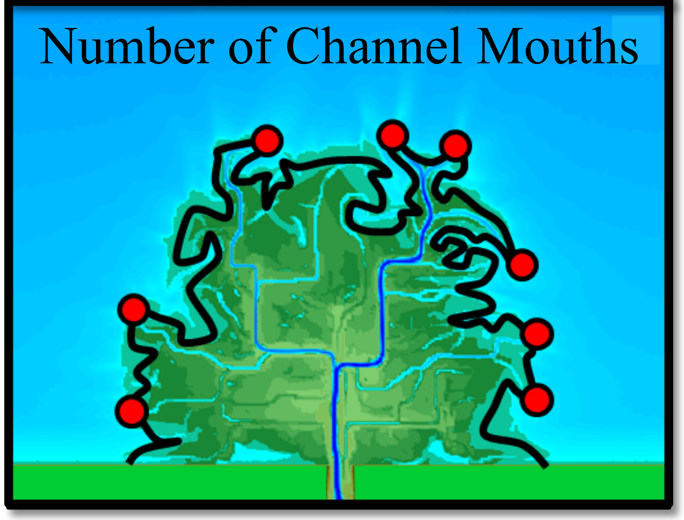
Delta morphology varies by topset gradient, number of active channel mouths, delta front rugosity, and delta shape

Average Topset Gradient

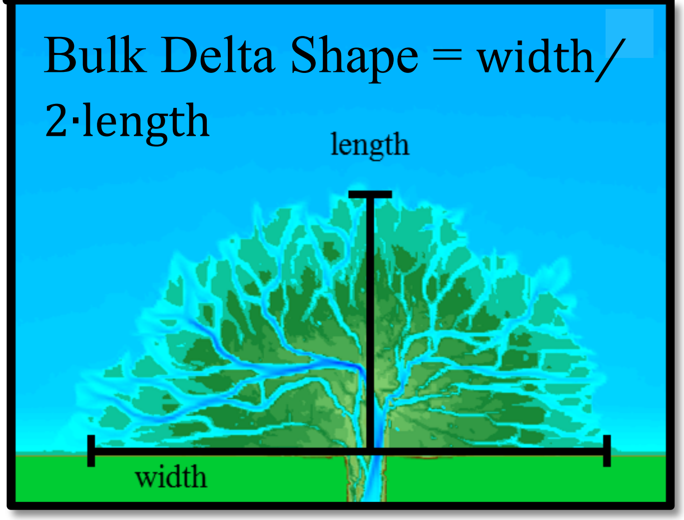


Delta Front Rugosity = delta front/ smoothed front



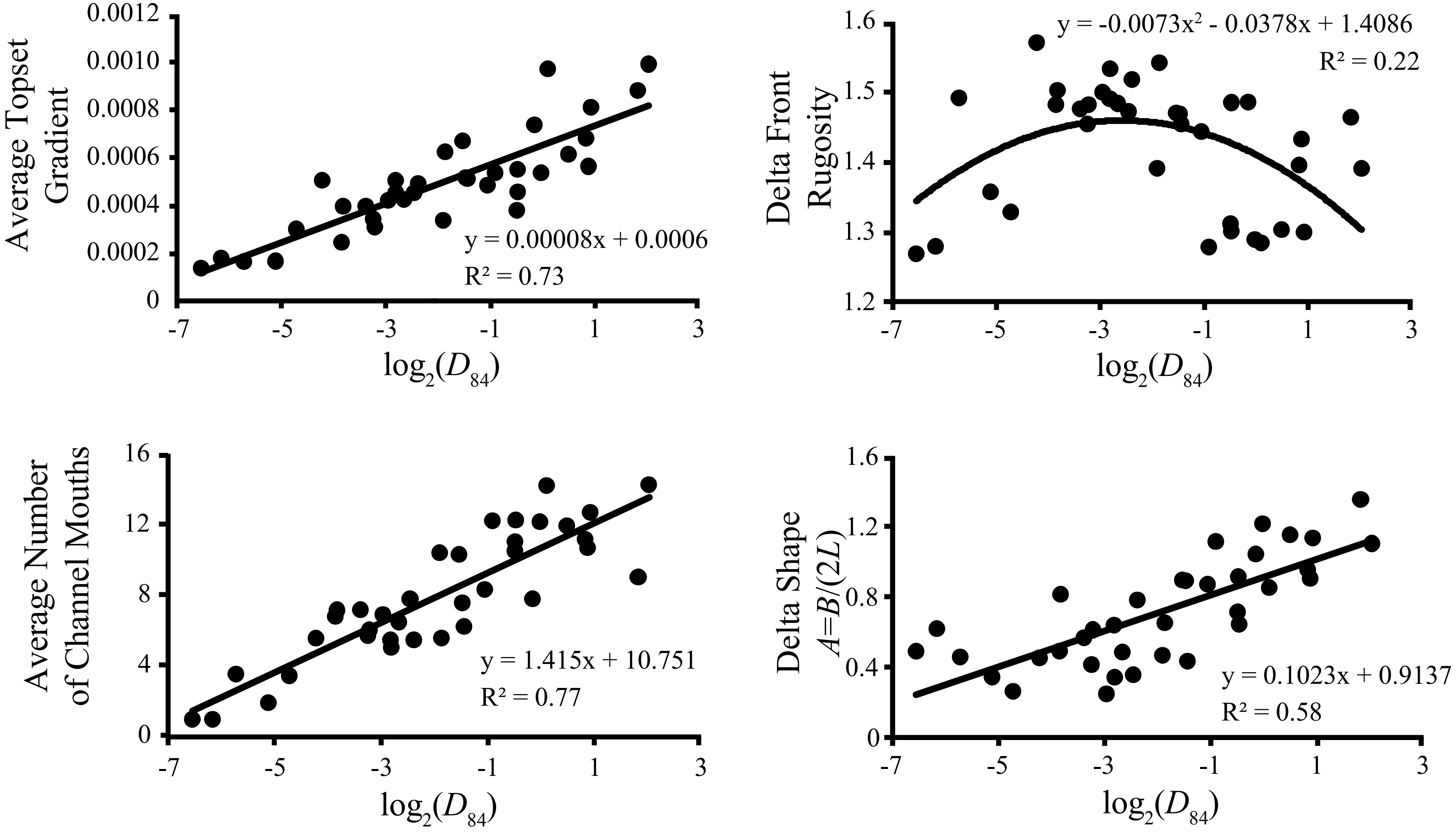


Number of Channel Mouths

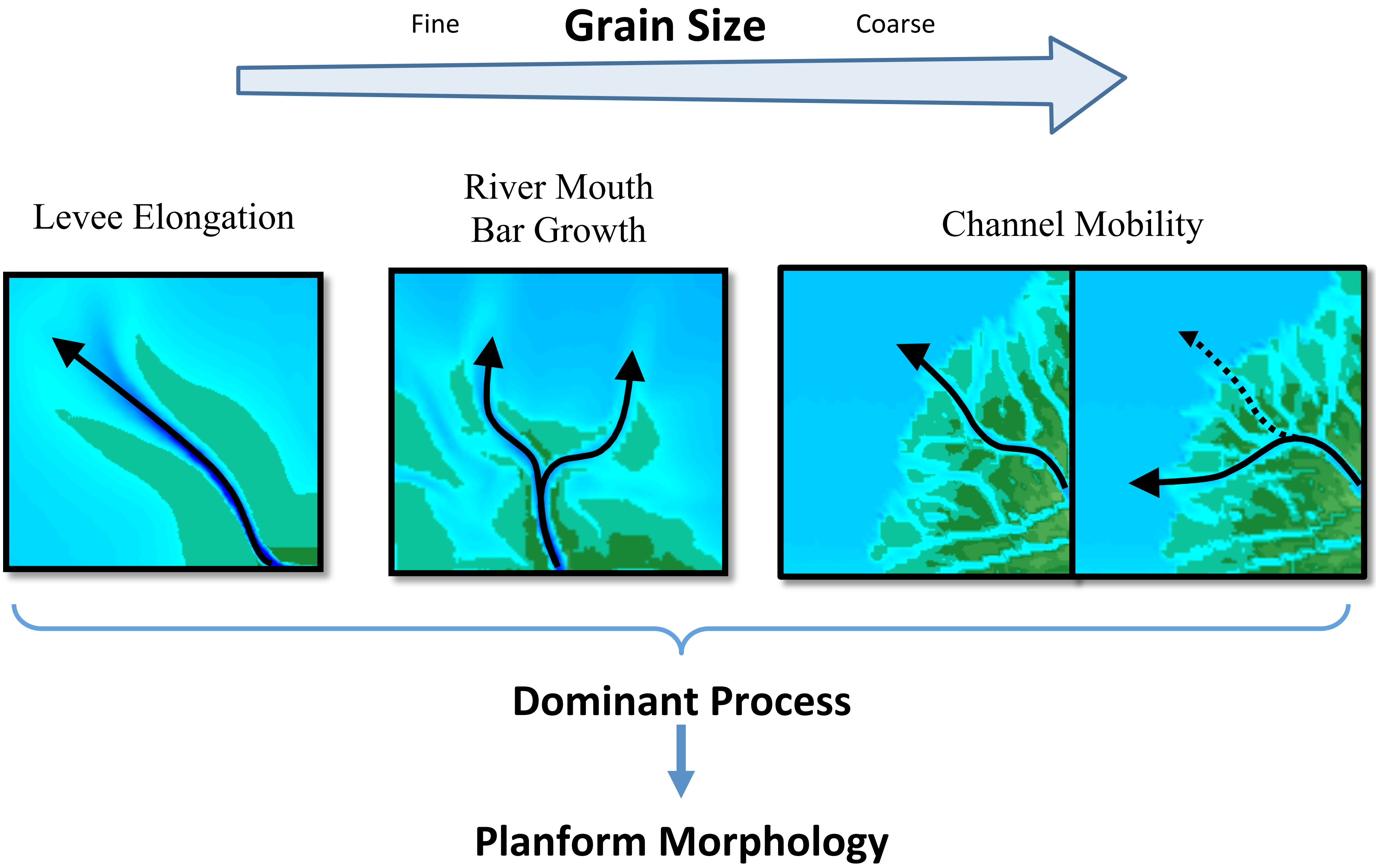


Bulk Delta Shape = width/ 2·length

Delta morphology varies by topset gradient, number of active channel mouths, delta front rugosity, and delta shape



A new, process-based model for delta morphology



Fine **Grain Size** Coarse

Levee Elongation

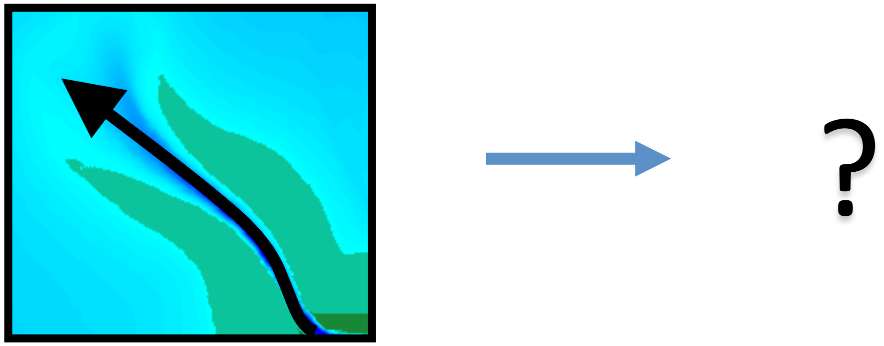
River Mouth
Bar Growth

Channel Mobility

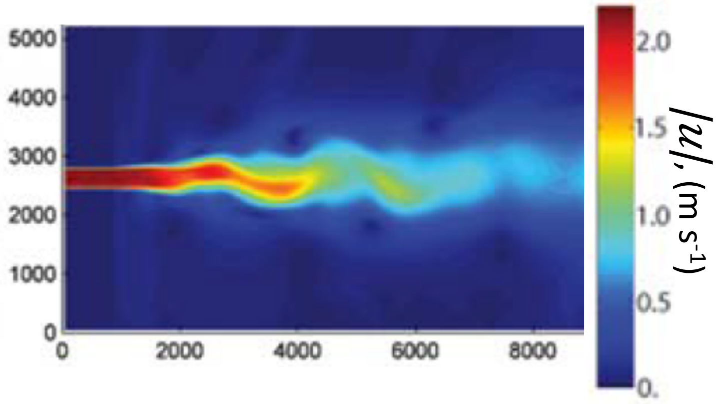
Dominant Process

Planform Morphology

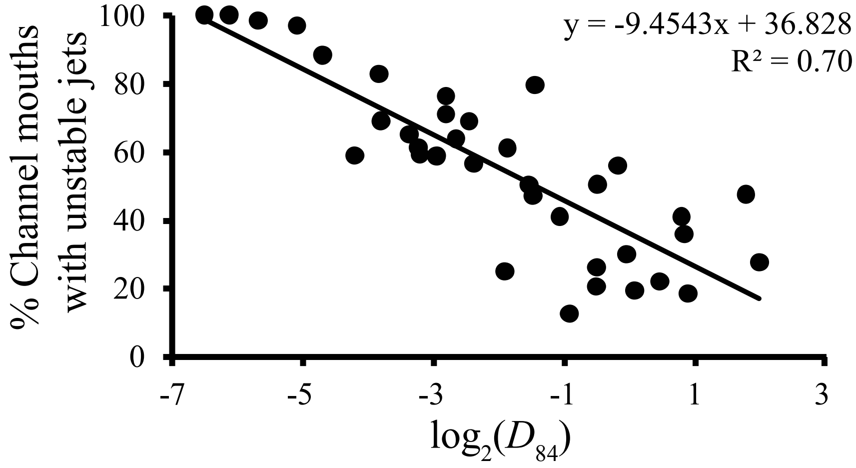
Levee elongation is enhanced by unstable turbulent jets, which become more common as grain size decreases



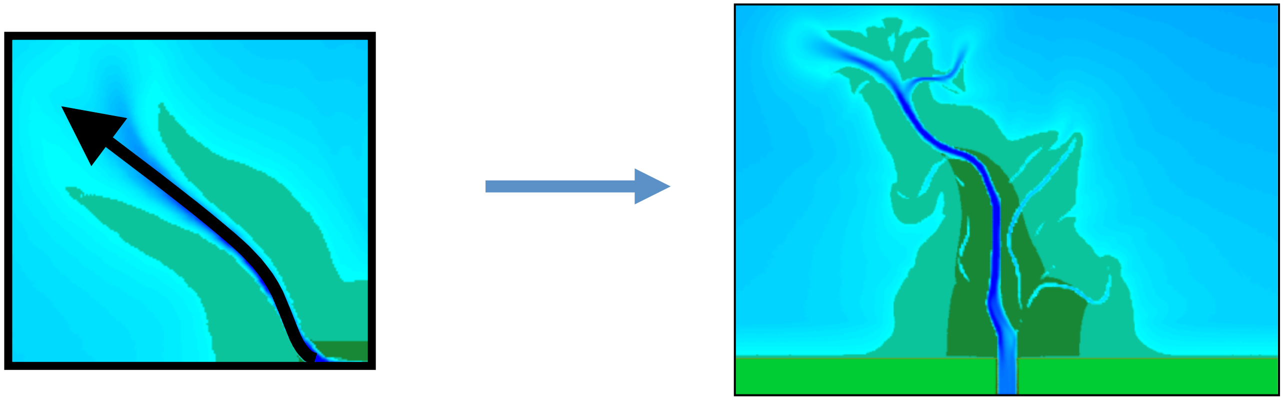
Jet instability criterion $\sim$ f (aspect ratio, velocity)

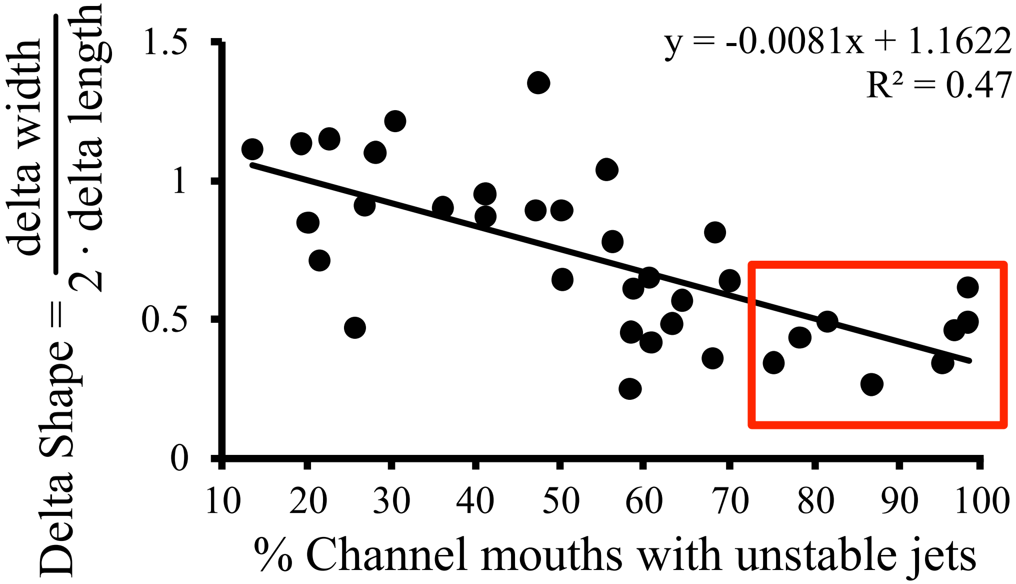


[*Canestrelli et al.*, 2014]

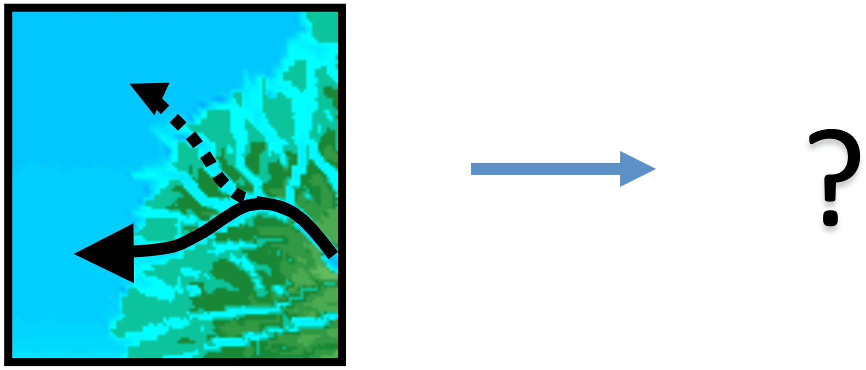


Deltas dominated by levee elongation create elongate planform morphologies

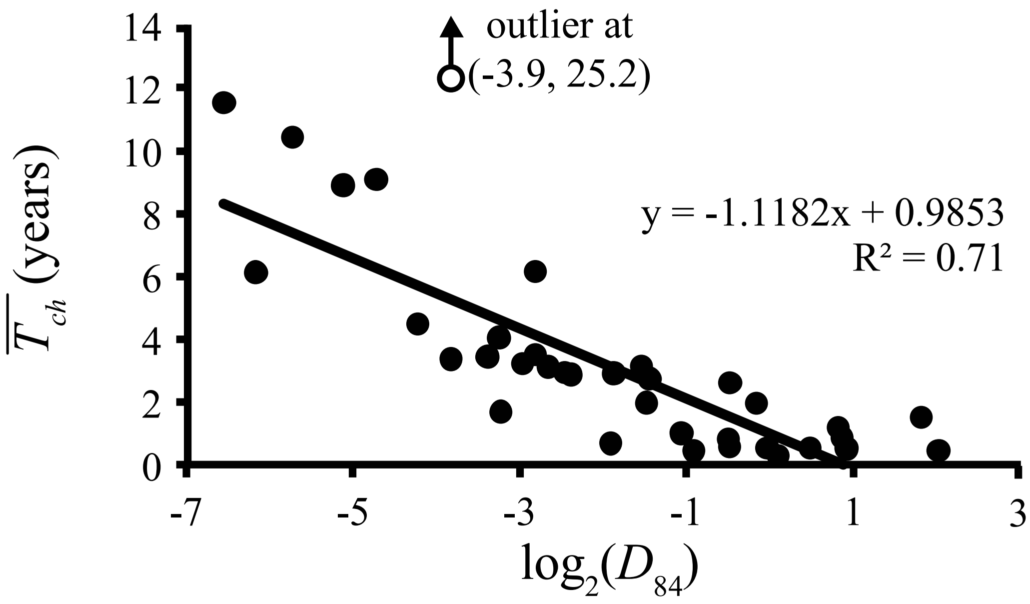




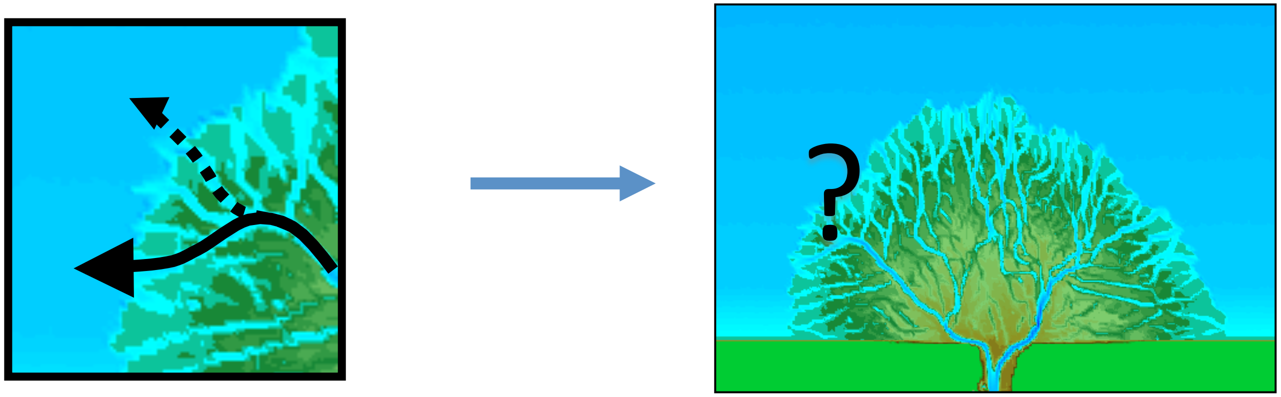
Channels become more mobile as grain size increases, due to the process of channel avulsion

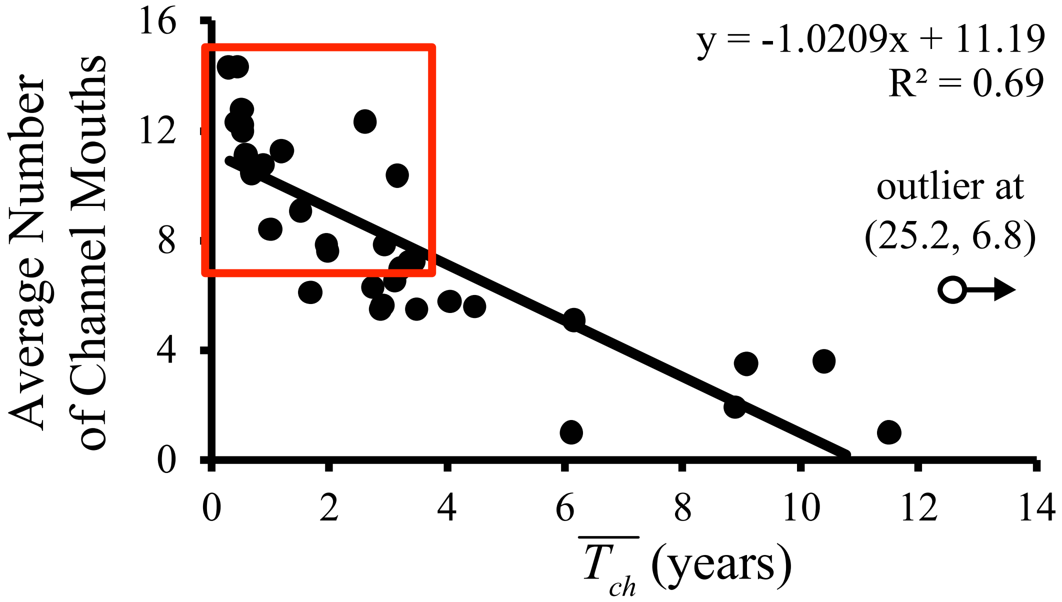


Measured channel life time scale ($T{\downarrow}ch$) ≈ Avulsion time scale

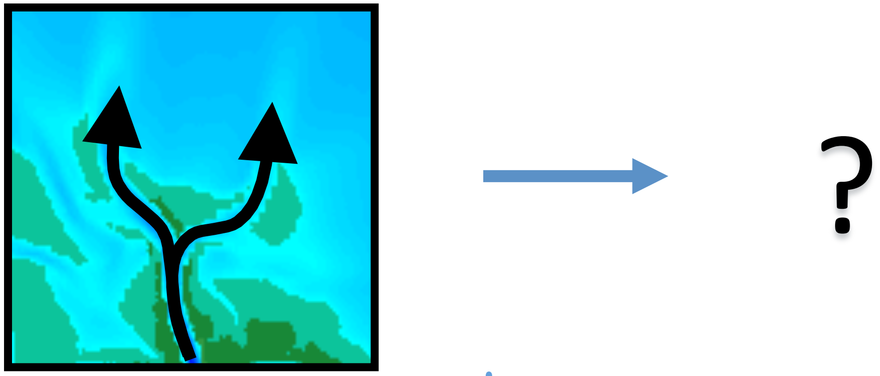


Deltas dominated by channel avulsion create a large number of channel mouths





Deltas dominated by mouth bar growth must construct mouth bars before channels avulse to a new location



$$\text{Mouth bar growth time scale } (T_{rmb}) = \frac{\text{Mouth Bar Volume}}{\text{Depositional Sediment Flux}} = \frac{0.6b^{2}\,h/\beta}{Q_{s}}$$

b: average channel width, m;

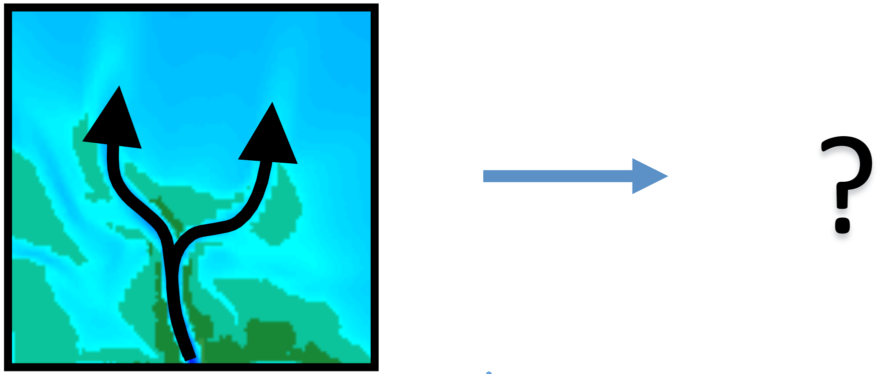
h: average channel depth, m;

β: mouth bar sediment supply correction factor;

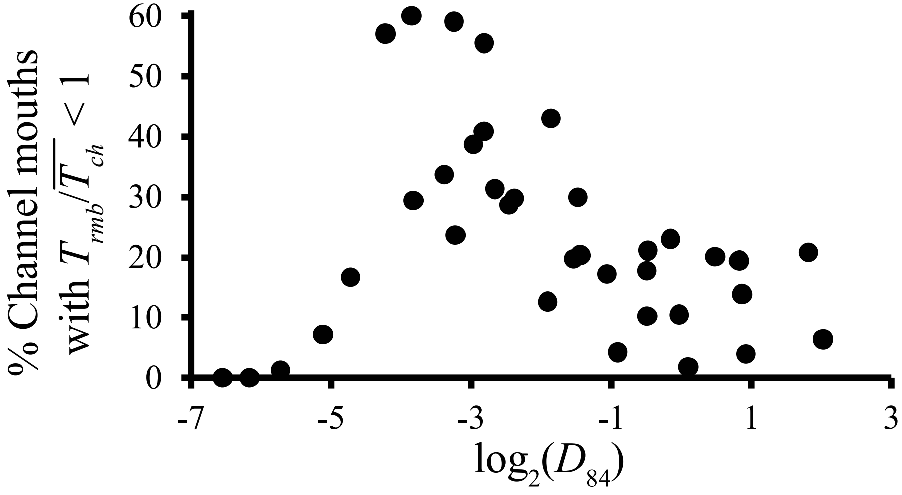
Q_{s} : sediment flux, $m^3\ yr^{-1}$;

[modified from *Jerolmack and Swenson*, 2007]

Mouth bar growth is faster than channel avulsion for intermediate grain sizes



$$\text{Mouth bar growth time scale } (T_{rmb}) = \frac{\text{Mouth Bar Volume}}{\text{Depositional Sediment Flux}} = \frac{0.6b^2 h/\beta}{Q_s}$$



b: average channel width, m;

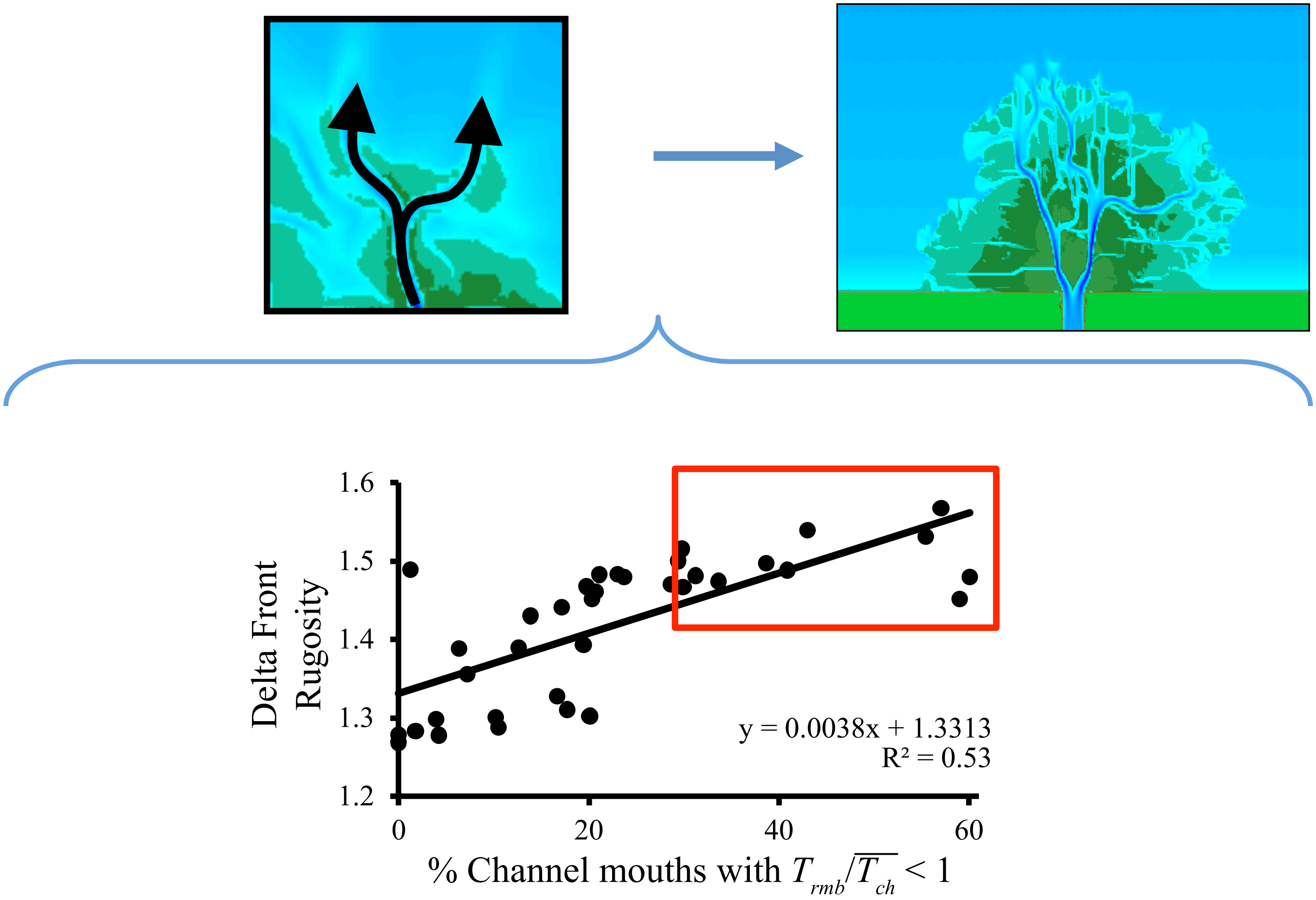
h: average channel depth, m;

β: mouth bar sediment supply correction factor;

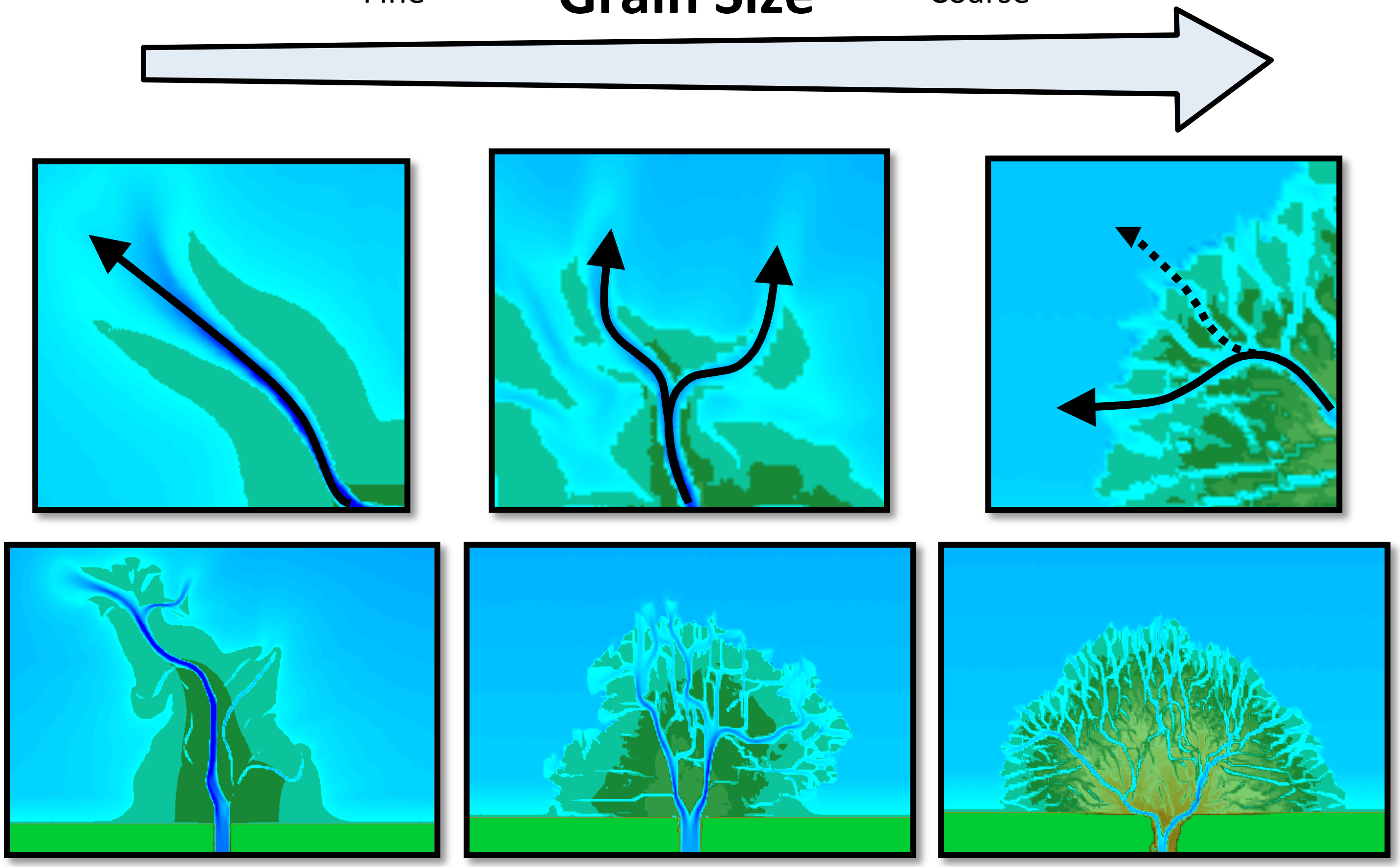
Q_s : sediment flux, $m^3\ yr^{-1}$;

[modified from *Jerolmack and Swenson*, 2007]

Deltas dominated by mouth bar growth create rugose delta fronts



CONCLUSION: A process-based model for grain size effects on delta growth



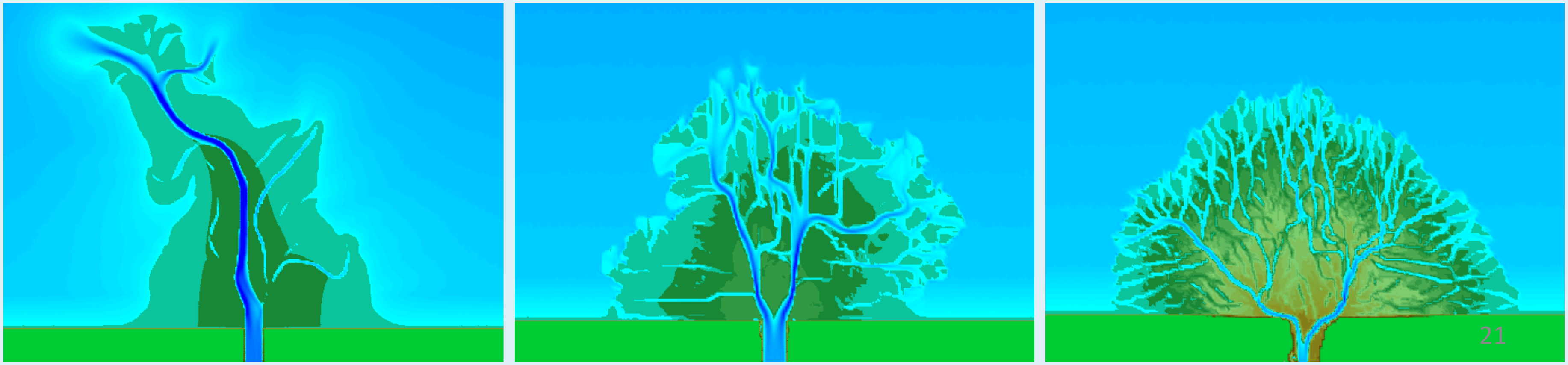
Fine **Grain Size** Coarse

Dominant Process

Morphology

Channel Mouths:	*Few*	*Intermediate*	*Many*
Delta Front:	*Smooth*	*Rugose*	*Relatively Smooth*
Planform Shape:	*Elongate*	*Semi-circular*	*Semi-circular*

Thank you



Notation

b	channel width, m;
B	delta width, m;
C	Chézy value, $m^{1/2}$ s^{-1};
D_{50}	median grain size, mm;
D_{84}	representative dominant grain size, mm;
g	acceleration due to gravity, m s^{-2};
h	channel depth, m;
h	average channel depth, m;
L	delta length, m;
P_m:P_r	proxy for ratio of marine power to river power, nondimensional;
Q	water discharge, m^3 s^{-1};
Q_s	total sediment discharge exiting channel mouth, m^3 s^{-1};
t	current time in delta growth, yr;
T	total modeled delta lifetime, yr;
T_A	predicted channel avulsion time scale, yr;
$T\downarrow ch$	measured average channel time scale, yr;
T_{rmb}	theoretical river mouth bar formation time scale, yr;
u	depth-averaged velocity, m s^{-1};
w_s	settling velocity, m s^{-1};
β	mouth bar sediment supply correction factor, nondimensional;
η	channel aggradation rate, m yr^{-1};
ν	kinematic viscosity coefficient of water, m^2 s^{-1};
σ	standard deviation of the grain-size distribution, ϕ;
ϕ	grain size phi value, nondimensional;
ψ	superelevation of a channel relative to *h* for an avulsion to occur, nondimensional;

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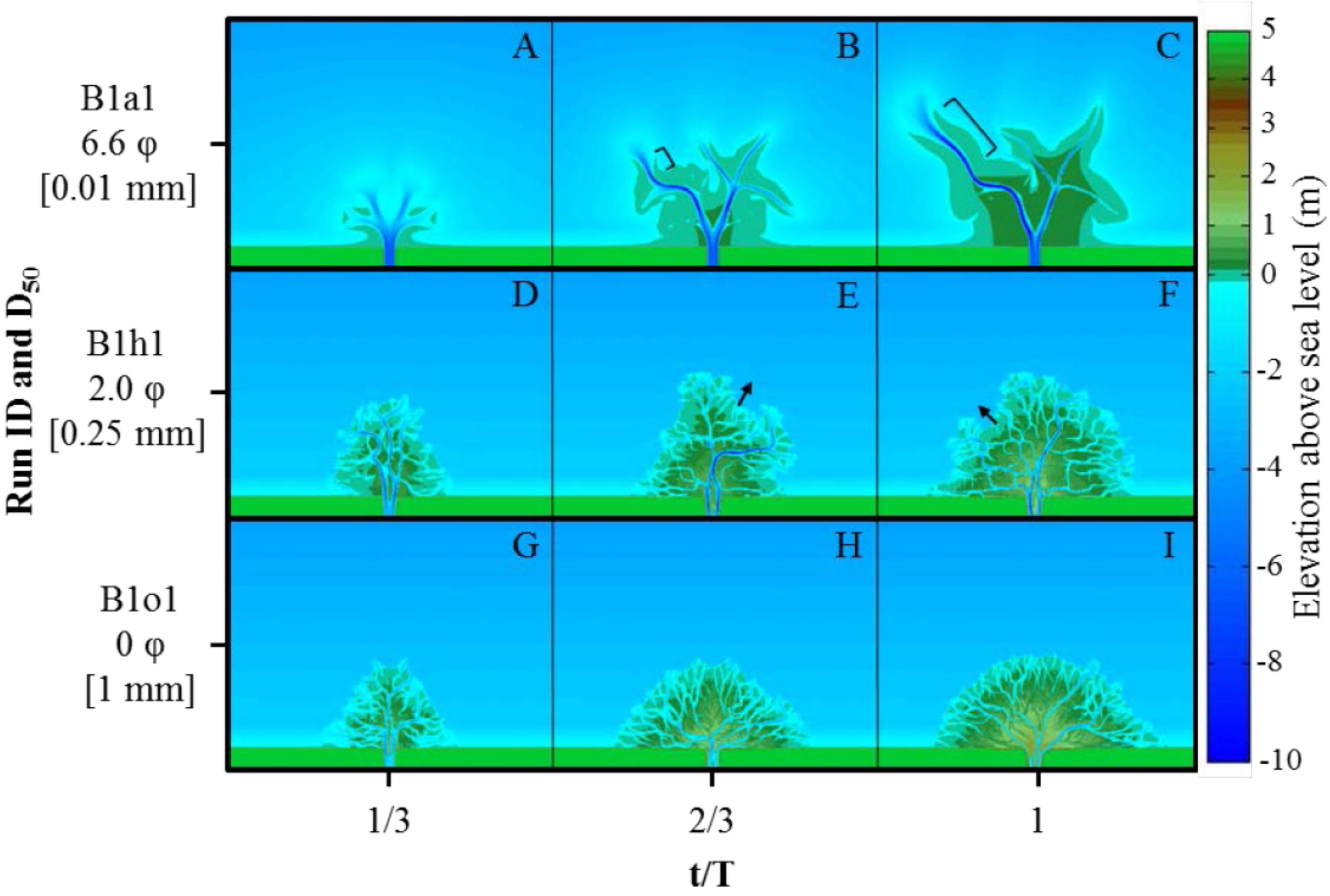
Run ID and D$_{50}$
B1a1
6.6 φ
[0.01 mm]
B1h1
2.0 φ
[0.25 mm]
B1o1
0 φ
[1 mm]
A
B
C
D
E
F
G
H
I
1/3
2/3
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5
4
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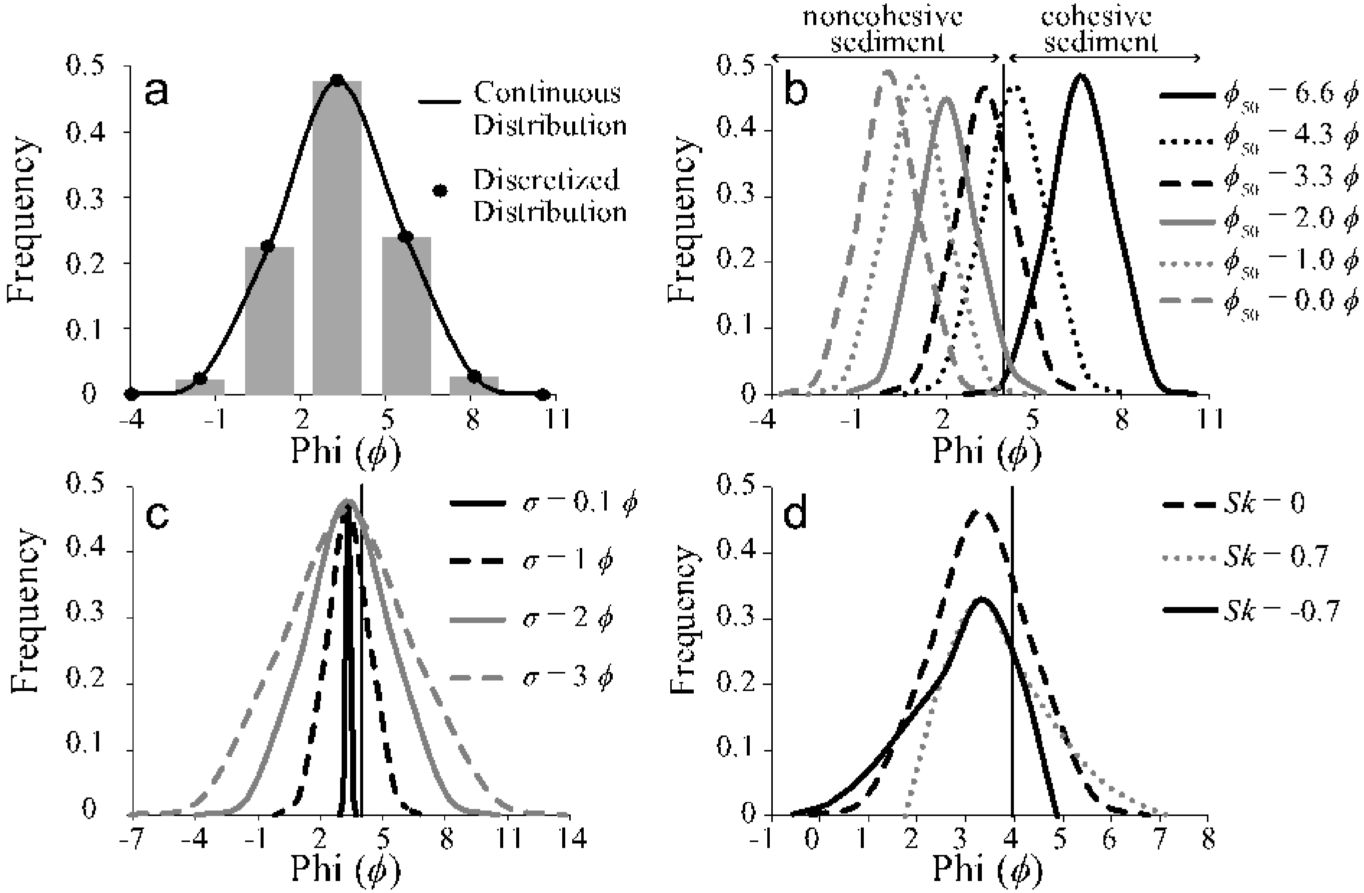
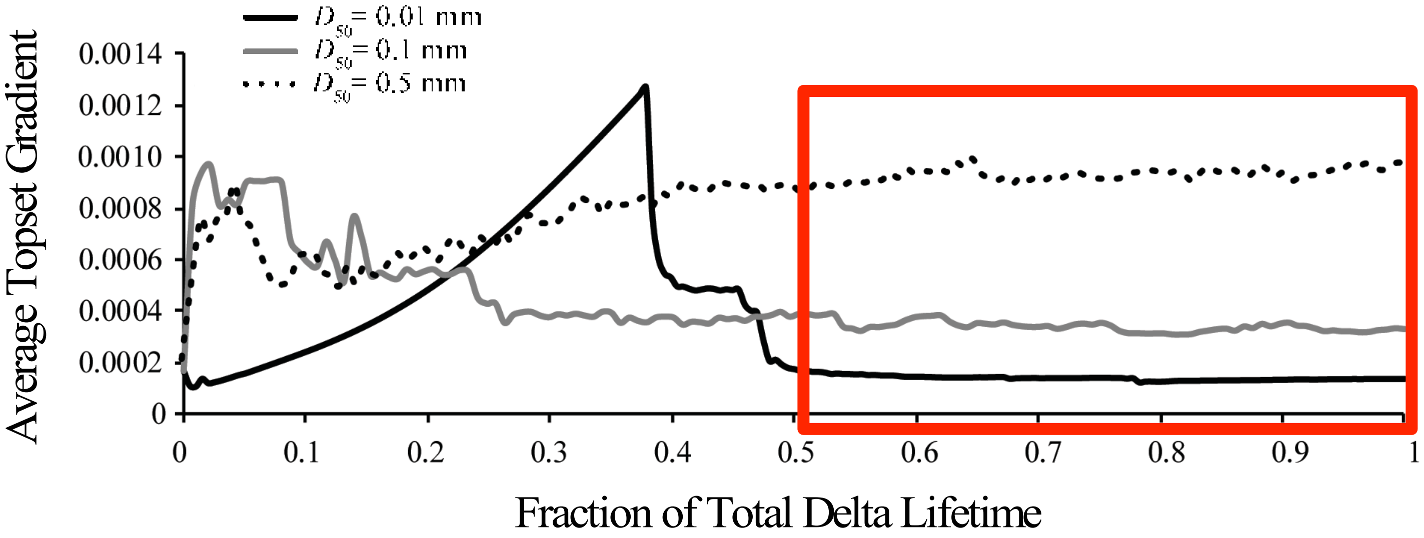
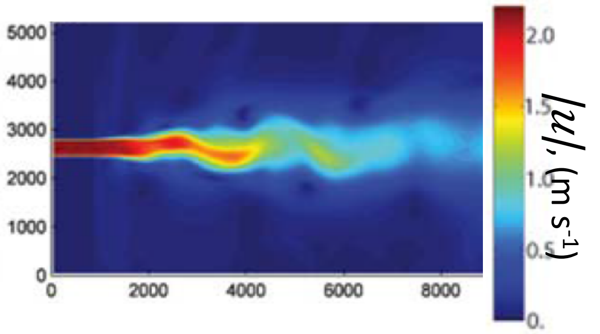
2
1
0
-2
-4
-6
-8
-10
Elevation above sea level (m)


a
Frequency
0.5
0.4
0.3
0.2
0.1
0
-4
-1
2
5
8
11
Phi (φ)
Continuous Distribution
Discretized Distribution
b
noncohesive sediment
cohesive sediment
$\phi_{50} = 6.6\ \phi$
$\phi_{50} = 4.3\ \phi$
$\phi_{50} = 3.3\ \phi$
$\phi_{50} = 2.0\ \phi$
$\phi_{50} = 1.0\ \phi$
$\phi_{50} = 0.0\ \phi$
Frequency
Phi (φ)
c
$\sigma = 0.1\ \phi$
$\sigma = 1\ \phi$
$\sigma = 2\ \phi$
$\sigma = 3\ \phi$
-7
-4
-1
2
5
8
11
14
Frequency
Phi (φ)
d
$Sk = 0$
$Sk = 0.7$
$Sk = -0.7$
-1
0
1
2
3
4
5
6
7
8
Frequency
Phi (φ)

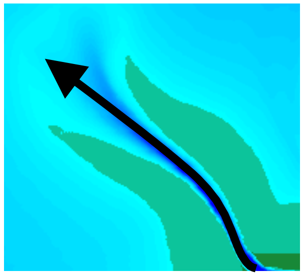
Steeper equilibrium gradients require higher aggradation rates per unit length of progradation



Levee elongation is enhanced by unstable turbulent jets, which become more common as grain size decreases

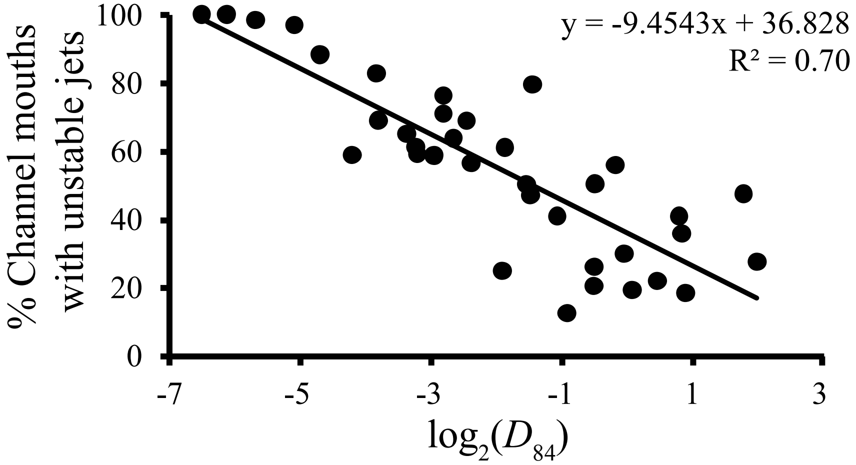


[*Canestrelli et al.*, 2014]



?

Jet instability criterion = $\frac{g}{2C^2}\frac{b}{h} < 0.0013\left(\frac{ub}{\nu}\right)^{0.235}$



g : acceleration due to gravity, m s^{-2};

C: Chézy friction value, m$^{1/2}$ s^{-1} ;

b: average channel width, m;

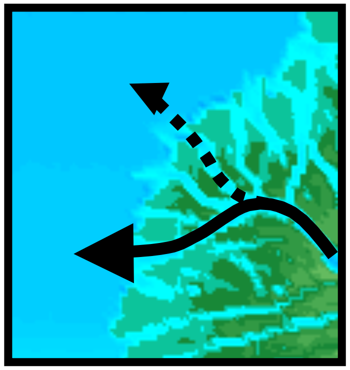
h: average channel depth, m;

u: average channel mouth velocity, m s^{-1};

ν: kinematic viscosity of water, m^2 s^{-1};

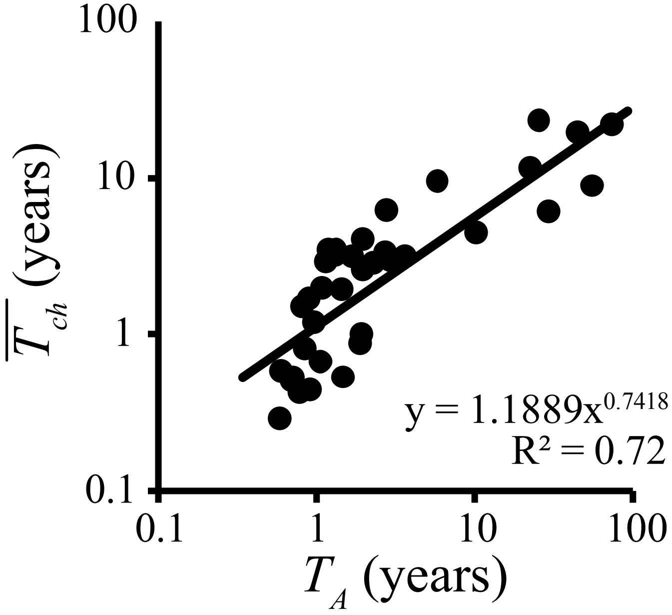
[modified from *Canestrelli et al.*, 2014]

Channels become more mobile as grain size increases, due to aggradation-driven channel avulsion

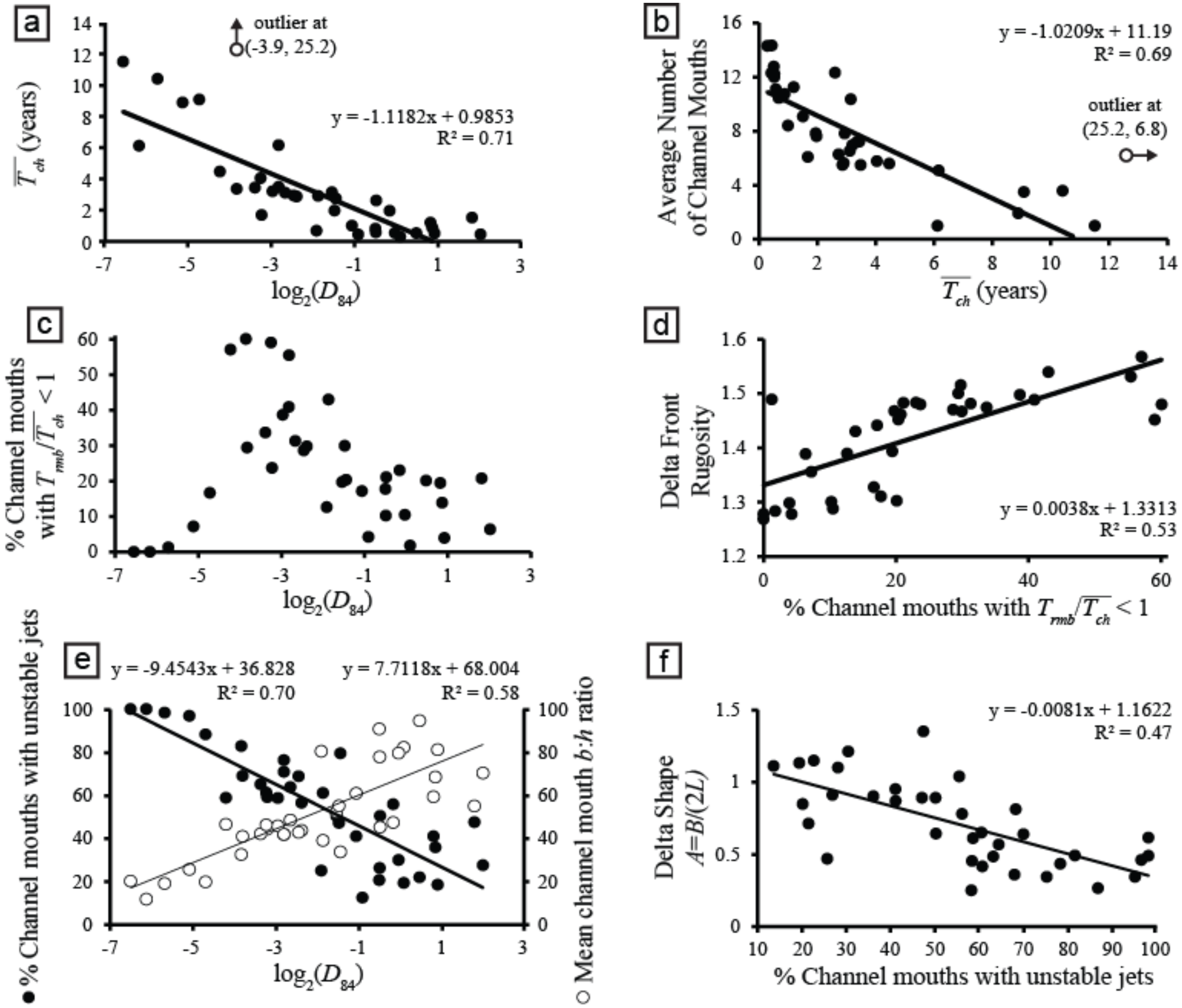


→ ?

Measured channel life time scale ($T\downarrow ch$) ≈ Predicted theoretical avulsion time scale ($T\downarrow A$) $= \Psi h / \eta$



Ψ : threshold channel superelevation, 0.74;
h : average channel depth, m;
η : channel aggradation rate, m yr^{-1};
[modified from *Jerolmack and Mohrig*, 2007]


a
outlier at (-3.9, 25.2)
y = -1.1182x + 0.9853
R² = 0.71
$\overline{T_{ch}}$ (years)
$\log_2(D_{84})$
b
y = -1.0209x + 11.19
R² = 0.69
outlier at (25.2, 6.8)
Average Number of Channel Mouths
$\overline{T_{ch}}$ (years)
c
% Channel mouths with $T_{rmb}/\overline{T_{ch}} < 1$
$\log_2(D_{84})$
d
y = 0.0038x + 1.3313
R² = 0.53
Delta Front Rugosity
% Channel mouths with $T_{rmb}/\overline{T_{ch}} < 1$
e
y = -9.4543x + 36.828
R² = 0.70
y = 7.7118x + 68.004
R² = 0.58
● % Channel mouths with unstable jets
○ Mean channel mouth b:h ratio
$\log_2(D_{84})$
f
y = -0.0081x + 1.1622
R² = 0.47
Delta Shape $A=B/(2L)$
% Channel mouths with unstable jets